Chapter 2
Risk Assessment

Abstract   There is no one widely accepted definition of risk. In fact, the meaning of
the term risk is widely debated in literature (Holton 2004; Knight in Risk, uncer-
tainty, and profit. Hart, Schaffner & Marx; Houghton Mifflin Co. Boston, MA,
1921). However, risk is usually associated with uncertainty. In terms of system life
cycle, risk is associated with uncertainty and opportunities related to cost, schedule,
and performance (INCOSE in Systems engineering handbook: a guide for system
life cycle processes and activities. INCOSE, San Diego, CA, 2011). In the area of
decision making, risk is associated with probabilities of unknown outcomes
(Gibson et al. in How to do systems analysis. Wiley-Interscience, Hoboken, NJ,
2007). Nonetheless, a classical view of risk considers probability of occurrence of
an event that could halt operations and consequences of such an event (ASCE in
Guiding Principles for the Nation’s Critical Infrastructure. American Society of
Civil Engineers, Reston, VA, 2009). The comprehensive analysis which consists of
an objective evaluation of risk in which assumptions and uncertainties are clearly
considered and presented is referred to as risk assessment. Risk assessment involves
the determination of quantitative or qualitative estimation of risk related to a
concrete situation and a recognized threat or hazard.

2.1 Risk Assessment in Hazmat Transportation

In the particular case of risk assessment in the transportation of hazardous (i.e. hazmat)
materials, the calculations of probability of occurrence of the disruptive event (the loss
of containment) and of the consequences of such event (the impact on the public and
the environment) play a critical role. Risk assessment typically is the basis for con-
cepts of risk classifications (e.g., acceptable–unacceptable) and is instrumental in
areas of decision making, resource allocation, and policy change. There are several
methods for risk assessment that may differ from industry to industry, especially based
on the type of risk involved (e.g., environmental, ecological, and public health). Some
domains (e.g., nuclear, aerospace, oil, rail, and military) have a long standing in the
concept of risk, and their risk assessment methods tend to be more advanced.
Risk assessment in hazmat is unique; an incident involving a transportation mode (e.g., vehicle or train) carrying hazmat cargo can produce undesirable short- and long-term effects on human health, environment, and property because of the possible release of toxic material and effects can be felt beyond an immediate area of an accident. Figure 2.1 attempts to illustrate this point by indicating that effects on an accident can be felt beyond the location of an impact. The impact location is the point of an accident and is represented by the center of the circle. From this simple illustration, the relevance of including spatial data and properties of a hazmat starts to become evident. Moreover, research suggested that 87 % of reported accidents (Major Hazard Incident Data Service—a major database) involve release hazmat (Oggero et al. 2006). Indeed, a hazmat event could be referred to as Low Probability High Consequence.

2.1.1 The Hot Spots Approach

In many models, risk is computed without considering spatial information which characterizes transportation routes. This issue can be addressed through a consideration of hot spots (Gheorghe et al. 2003, 2005; Riegel 2015). The concept of ‘hot spots’ introduces route spatial characteristics and influences the computation of the probability and consequence assessment in the case of a loss of containment (LOC) accident (Gheorghe et al. 2003). The hot spots method is a practical and intuitive solution for developing accident scenarios based on a more detailed characterization of the determining risk factors that can be encountered along a transportation route (Gheorghe et al. 2004). The relationship between LOC probability, LOC consequence, and risk is presented in Fig. 2.2. When the concept of hot spots is deployed, several measures that would be ignored during a traditional approach are brought at the forefront of the analysis. In the case of transportation, especially land transportation, a logical conjugation of one hot spot might be defined in terms of a set of predefined criteria. This criterion might involve:

- The existence of at least one of the sensitive infrastructure components, and/or
- Crossing a given type of land use, and/or
Population density which could be indicated in terms of excess of a given threshold.

The sensitive infrastructure components can be identified based on road and rail accident statistics. This approach leads to the identification of the most frequent spatial characteristics in the proximity of the accidents. Identified ‘sensitive’ infrastructure components include the following: motorway rest areas, motorway entrance/exits, bridges, passages, tunnels, high-voltage line crossings, crossings, traffic jam areas, sharp curves areas and gas stations for road transportation, and station, signal, switch, bridge, passage and tunnels for rail transportation, respectively (Gheorghe et al. 2003).

The hot spots approach allows the multicriteria risk characterization of the transportation routes, by taking into account the risk contributing factors given by

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**Fig. 2** Relationship between probability, consequence, and risk

- *Population density* which could be indicated in terms of excess of a given threshold.
the infrastructure, environment, and population. The first step in applying this method is identifying the areas along the route where the definition criteria of a hot spot are met. In this case, a route is described by a list of hot spots (i.e., locations with a higher risk of accidents). The second phase involves performing statistics in every hot spot, over a circular area determined by a relevant radius that equals the relevant radius of the considered physical effect (e.g., relevant radius for BLEVE—boiling liquid expanding vapor explosion). The gathered data are the basis for a hot spot risk index. Finally, the hot spots are then sorted by the risk indices and placed in risk basins defined in accordance with the risk perception of the analyst.

2.1.1.1 Representing Risk in the Hot Spot Method: The Risk Matrix

The assessment of the hot spots on a transportation segment leads to the creation of segment risk report (i.e., a listing of critical points along a given segment). A risk report is a source of the segment’s risk pattern which is a holistic representation of the risk associated with the analyzed segment. Creating a risk pattern is a two-step process which involves: (1) sorting and classifying the hot spots as either hot, warm, or acceptable and (2) building a risk matrix.

Sorting and classifying is done through (a) the characteristic probability of LOC accident and (b) the consequence assessment which is defined in terms of health impact quantified by the number of deaths as a result of an accident at the particular hot spot. A classification of a hot spot (i.e., hot, warm, and acceptable) is done by setting the threshold values for both probability and lethality. These values are a reflection of the risk perception by the analyst which is in accordance with previous research (Clemson 1984; Katina 2015; Quade 1980; Warfield 1976). In the second step, the building of a risk matrix is done through probability against consequence measure and populating it with the identified hot spots. This creates an interval classification of the probabilities and consequences which is conducive in effect in defining three risk basins within the risk matrix.

2.1.2 The Statistical Approach

2.1.2.1 The Framework

The framework starts from an innovative statistical approach which was introduced in Gheorghe et al. (2000). The method was originally developed for risk assessment of hazmat transportation by rail. The validity of the model in the road transportation case, as well as its potential applicability in other transportation domains, such as inland waters, has been confirmed in different quantitative assessments undertaken at the Swiss Federal Institute of Technology (ETH Zürich), Zurich, Switzerland.

This model targets the representation of the risk associated with an activity by the cumulative frequency of the consequence indicators. In the case of transportation of hazardous materials, this is referred to as the representation of hazmat
transportation by the cumulative frequency of fatalities (CFF). This model requires an intensive use of the hot spots method in conjunction with a circumstantial database for statistical analysis of the transportation segment vicinity. The process of computing the CCF involves:

(a) the identification of the route characteristic hot spots,
(b) setting up a complex source term containing a complete set of scenarios corresponding to different substance components of the transportation and distinct release classes (from small to complete release), and
(c) health and environmental impact assessment (in the form of cadastral statistics) accompanied by the LOC probability assessment for each of the plausible scenarios.

The following section elaborates on the model. Appendix C elaborates on need for hazmat database development and provides development guidelines.

2.1.2.2 The Statistical Method

This section elaborates on the nature of the problem statement along with the conceptual aspects and the computational algorithm for obtaining the cumulative frequency of fatalities (CFF). Note that the objective of the assessment is the computation of the CFF. Risk associated with a given transport system is then characterized by the complementary CCFF which is closely related to CCDT—complementary cumulative distribution function.

The Scenarios
For a given case, the following holds:

- CFF refers to a set of N scenarios
- One scenario is characterized by:
  - The substance: A subject of transportation and LOC accident. Each substance is in turn characterized by a vector of physical and chemical properties. These are necessary for the consequence assessment phase.
  - One release category: A classification of small, medium, large, and the corresponding quantities such as kilogram (kg).
  - One physical effect: These can include, among others, pool fire, BLEVE, and toxicity along with the consideration of the physical effects of the substance. Each of the identified possible effects is then assessed using a corresponding method of consequence assessment. The results are provided in: (i) Lethality Percentage as function of Distance and (ii) the characteristic effect radius—the distance up to which the lethality percentage exceeds zero (0).
  - A list of hot spots along a given route is always identified using the hot spots approach.
Obtaining the CFF based on a scenarios set

To construct the CFF, one has to compute for each scenario $j$ ($j = 1 \ldots N$, $N$—number of scenarios) the two variables:

1. the expected number of fatalities, ($NF_j$) and
2. the expected frequency of occurrence, ($SF_j$);

If $NF_j$ and $SF_j$ are known, we proceed by:

- building the NFSF matrix ($NFSF \in \mathbb{R}^{N \times 2}$) as having $NF_j$ and $SF_j$ as columns. That is,

$$NFSF(j, 1) = NF_j \text{ and } NFSF(j, 2) = SF_j$$

- sorting the NFSF descending by $NF_j$
- computing the cumulative frequency for each scenario as

$$CFF(i) \sum_{j=1}^{i} SF_j$$ \hspace{1cm} (2.1)

- Build an $X$–$Y$ diagram as $\lg(CFF_j)$ versus $\lg(NF_j)$, $j = 1 \ldots N$. The polyline as indicated in Fig. 2.3 is thus obtained using the statistical method.

The Process

Phase 1: Identification of hot spots and the statistics

This phase implies the identification of the hot spots along a given transportation segment and the computation of the corresponding NF and SF values. Once a hot spot (i.e. a location along the route which meet the hot spot definition criteria) is identified, NF and SF are computed using the following scheme:

1. for each point $p$ of the circular area centered at the hot spot location and having a radius equal to a given scenario’s characteristic effect radius:
   (a) get the distance, $d$, from the hot spot to point $p$;
(b) get the expected lethality percentage at distance \(d\) by interpolating the scenario characteristic lethality percentage using distance correlation table;
(c) get the expected number of fatalities from the lethality percentage and the effective number of individuals exposed.

2. compute the expected number of fatalities at hot spot \(i\) (\(NF_i\)) by summing up the partial results obtained above;
3. the hot spot characteristic LOC frequency is computed by multiplying the scenario characteristic frequency with the corresponding value from the LOC probability pattern (LCPP) matrix. The LCPP expresses the assumption that the LOC event is influenced by the combination of a given land use and the type of infrastructure (i.e., object/objects) at the hot spot location. The values of LCPP are assumed a priori and can be obtained from accident statistics and/or using expert judgment.

**Phase 2: Lethality number mitigation factors**

It has been shown that models tend to provide over-conservative results especially when it comes to number of fatalities that could result from a LOC accident (Vamanu 2006). In reality, however, there are numerous factors that could contribute to mitigating the effects of LOC. For example, if one is considering the lethality number caused by heat radiation, one can easily notice that the number of casualties is significantly higher when the scenario accident occurs in open space as opposed to a residential area. The value of lethality is reduced since there is a shielding effect that is attributed to the presence of buildings. However, if the same event takes place in an industrial area, the lethality number could be higher because of a possible domino effect.

In this case, the statistical method provides several means of tuning up the assessment in order to reflect this logic. This is done through a consideration of:

**Angular sectors mitigation factors**

In the case of fire and explosion, it is natural to assume that the effects will spread into a circular motion. However, this is not plausible when one considers toxicity because of atmospheric dispersion. Thus, one can reasonably conclude that wind direction plays a significant role in the validity of the assessment. The wind direction is taken into account using the following approach: Split the circular area centered at the accident location in a number \(m\) (e.g., \(m = 16\)) of angular sectors, \(S_m\). Each sector \((S_i)\) is given a weight \((w_i)\) in accordance with the percentage of the time the wind blows in the direction within the \(S_i\) boundaries. The adjusted number of fatalities would then be given by:

\[
NF' = \sum_{i=1}^{m} NF_i * w_i
\]

where \(NF_i\) is the number of fatalities in sector \(i\).
Source term aggravation/mitigation factors

These factors adjust the scenario characteristic effect radius. These factors are defined taking into account the substance and its mass quantity.

Circumstantial aggravation/mitigation factors

These factors adjust the lethality number provided by the analytical models. The factors are a defined function of:

- the land-use characteristics (e.g., the presence in the vicinity of flammable objects as opposed with the presence of fire proof materials);
- the daytime period (e.g., rush hour as opposed to night time);
- the weather; and
- the physical effects.

2.2 Extension of the Risk Assessment Methodology for Multimodal Transportation

Fundamentally, hazmat transportation for rail and road transportation can be treated separately. This is primarily due to differences in the mechanics of occurrence of a LOC accident. However, for a holistic risk assessment, an extension of the assessment methodology is required to enable coping with complex transportation schemes which might involve different segments and conditions (Gheorghe et al. 2006).

2.2.1 The ‘Hot Spot’ Method

The way the risk matrix is generated in the case of a singular transportation segment can be extended for assessing transportation routes and corridors. In this case, a route is defined as a sequence of continuous transportation segments along which the transportation may be performed in a multimodal way (either by rail or by road) and in different circumstances (i.e., different model variables). A transportation corridor is defined as a collection of routes, potentially disjoined, that form a fascicle of transportation routes.

An individual assessment of transportation routes yields a set of route characterization reports. When the ‘hot spot’ methodology is applied to each of the constituent segments, followed by grouping the individual results into a report, and development of a comprehensive risk matrix, one gets the risk configuration associated with the route and or the corridor, respectively. The following observations can be made: First, the practical implementation of such an approach comes with considerable challenges associated with managing high volumes of data.
Second, it is obvious that in the case of partially overlapping routes and corridors the location of some of the hot spots will be the same. This is determined through the hot spot definition criteria. In such a case, it is possible to have unfeasible results especially if there is always a consideration of the common hot spots each time they appear in different routes. A solution to this issue is to give the analyst the freedom to choose a representative hot spot, in accordance with analyst’s risk perception. Third, it is essential to consider hot spot cases in which there is a shared location but belonging to different transportation segments (e.g., rail and road). In such a case, both hot spots need to be taken into consideration.

### 2.2.2 The Statistical Method

Extending the statistical method for the multimodal case implies extending statistical method for transportation routes and statistical method for transportation corridors. Statistical method for transportation routes involves the following:

1. Building the NFSF matrix for each constituent segment of the route,
2. Centralizing the NFSF matrices into a route characteristic matrix NFSF\_route,
3. Computing the CFF for NFSF\_route.

Thus, one gets the CFF profile characteristic to the transportation route. The statistical method for transportation corridors involves the following:

1. Building the NFSF\_route matrix for each constituent route of the corridor,
2. Centralizing the NFSF matrices into a corridor characteristic matrix NFSF\_corridor,
3. Computing the CFF for NFSF\_corridor.

For managing the hot spots shared by different segments or routes, the same rules as in the case of the multimodal hot spots assessment should be followed.

### 2.2.3 The Complementary Cumulative Distribution Function as a Risk Expression of the Health Impact

Another way of processing the lethality percentage so as to lead to a risk-specific representation is the complementary cumulative distribution function (CCDF). The algorithm for CCDF can be sketched as follows (Gheorghe et al. 2003). It is assumed that the probability of one individual located at distance $x$ from the event to be affected by the event is equal to the percentage (perc.) of affected people (resulted from the consequence assessment) divided by 100.
Every perc. value obtained as function of distance is then normalized to the sum of all of the percentages, thus obtaining the probability distribution function. The following equations hold:

\[
\sum_{R_{\text{min}}}^{R_{\text{max}}} f(R) = 1 \tag{2.3}
\]

with \( f(R) \) the normalized perc. The cumulative distribution function is then computed as follows:

\[
\text{CCDF}(R) = \sum_{R_{\text{min}}}^{R} f(R) \tag{2.4}
\]

Equation (2.4) leads at the complementary cumulative function defined as follows:

\[
\text{CCDF}(R) = 1 - \text{CDF}(R) \tag{2.5}
\]

References


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